Agriculture, Ecosystems and Environment 254 (2018) 82–91

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Research Paper

Reducing losses but failing to sequester carbon in soils – the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya

Rolf Sommer*, Birthe Katharina Paul, John Mukalama, Job Kihara

International Center for Tropical Agriculture (CIAT), ICIPE Duduville Campus, Kasarani, P O Box 823-00621, Nairobi, Kenya

ARTICLE INFO

Keywords:
Climate change mitigation
Greenhouse gas emissions
Soil organic carbon
C-sink
4p1000

ABSTRACT

Agriculture is a global contributor to greenhouse gas emissions, causing climate change. Soil organic carbon (SOC) sequestration is seen as a pathway to climate change mitigation. But, long-term data on the actual contribution of tropical soils to SOC sequestration are largely absent. To contribute to filling this knowledge gap, we measured SOC in the top 15 cm over 12 years in two agronomic long-term trials in Western Kenya. These trials include various levels – from absence to full adoption – of two widely promoted sustainable agricultural management practices: Integrated Soil Fertility Management (ISFM; i.e. improved varieties, mineral fertilizer and organic matter/manure incorporation) and Conservation Agriculture (CA; improved varieties, mineral fertilizer, zero-tillage and crop residues retention). None of the tested ISFM and CA treatments turned out successful in sequestering SOC long-term. Instead, SOC decreased significantly over time in the vast majority of treatments. Expressed as annual averages, losses ranged between 0.11 and 0.37 t C ha^{-1} yr^{-1} in the CA long-term trial and 0.21 and 0.96 t C ha^{-1} yr^{-1} in the ISFM long-term trial. Long-term application of mineral N and P fertilizer did not mitigate SOC losses in both trials. Adopting zero-tillage and residue retention alone (as part of CA) could avoid SOC losses of on average 0.13 t C ha^{-1} yr^{-1}, while this was 0.26 t C ha^{-1} yr^{-1} in response to mere inclusion of manure as part of ISFM. However, cross-site comparison disclosed that initial SOC levels of the two trials were different, probably as a result of varying land use history. Such initial soil status was responsible for the bulk of the SOC losses and less so the various tested agronomic management practices. This means, while ISFM and CA in the humid tropical agro-ecosystem of Western Kenya contribute to climate change mitigation by reducing SOC losses, they do not help offsetting anthropogenic greenhouse gas emissions elsewhere.

1. Introduction

Agriculture contributes 14 % to global anthropogenic greenhouse gas (GHG) emissions, and another 17 % through land use change, making it a major cause of climate change (Smith et al., 2008). Rather than being part of the problem, agriculture is sought to become part of the solution to climate change (OECD, 2016). Increasing carbon (C) stocks in agricultural landscapes as a means to mitigate climate change gained significant momentum in global debate with the last Conferences of the Parties (22) of the UNFCCC. At best, such carbon sequestration includes above- and below-ground sinks (Smith, 2016). As far as soils are concerned, the 4p1000 Initiative (http://4p1000.org/) set an aspirational target to increase global soil organic carbon (SOC) amounts in the top 40 cm of soils by 4‰ per year. According to the underlying rough estimates, the global effect of such sequestration would be enormous, with a proclaimed potential to halt any further increase of CO_2 concentration in the atmosphere (Lal, 2016). The discussion around C sequestration in soils ranges back at least 15 years. Ever since, the actual achievable net C sequestration effects have been contested (Stockmann et al., 2013; Powlson et al., 2011; Sommer and de Pauw, 2011; Baker et al., 2007; Lal, 2003). Sommer and Bossio (2014) argued it will take time to adopt measures to increase the SOC content of soils, i.e. realistically not all soils can be turned into SOC sinks immediately. Also, an increase in SOC does not proceed linearly for many years, but SOC sequestration in upland soils usually levels off at some point in time, e.g. after 20–30 years (West and Six, 2007). Both processes combined suggest it is flimsy to determine a fixed amount of SOC that could be sequestered on an annual basis for years to come at global scale. Irrespectively, there are numerous studies that present fixed annual quantities that could technically be sequestered. Most of them simply multiply per-area sequestration rates (e.g. t C ha^{-1} yr^{-1}) with estimated areas, as shown for several country case studies by

* Corresponding author.
E-mail address: r.sommer@cgiar.org (R. Sommer).

https://doi.org/10.1016/j.agee.2017.11.004
Received 24 June 2017; Received in revised form 30 October 2017; Accepted 2 November 2017
Available online 22 November 2017
0167-8809/

Minasny et al. (2017). Other studies in addition exclude soils with supposedly less sequestration potential such as soils in arid environment, peatland and wetland soils, or distinguish between forest soils, agricultural soils and/or rangeland and agricultural soils (Minasny et al., 2017; Paustian et al., 2016; Wollenberg et al., 2016; Lal 2010, 2003; Smith et al., 2008). Calculated potentials of these studies range between mitigating around 5 to 15% (Smith et al., 2008; Paustian et al., 2004) up to fully offsetting anthropogenic emissions (4p1000).

Regardless of the exact amount of potential C sequestration, the underlying assumption is that there are viable management practices to turn soils into C-sinks. Conservation Agriculture (CA) and Integrated Soil Fertility Management (ISFM) are arguably the most well-known soil conserving techniques in the humid tropics of sub-Saharan Africa (SSA). They are said to sequester SOC if adopted in their entireness, but adoption numbers and acreage are lacking for SSA. ISFM refers to a judicious combination of mineral fertilizer and organic inputs together with improved germplasm and sound agronomy to reach higher crop productivity and resource use efficiency (Sanginga and Woomer, 2009). Although ISFM is argued to increase SOC (Bationo et al., 2007; Tittonell et al., 2007), long-term evidence is lacking. Conservation agriculture (CA) is built on three pillars – minimum soil disturbance (e.g. by zero-tillage), crop residue retention on the soil surface, and increased diversification through rotation and/or intercropping of different crop species (Hobbs et al., 2008). A number of studies have been measuring SOC under CA in the long-term. While clear sequestration benefits were observed in researcher-managed trials (Thierfelder et al., 2014; Verhulst et al., 2012), the signal was less clear in farmer's fields (Cheesman et al., 2016; Pittelkow et al., 2014; Powlson et al., 2014), and thus euphoria somewhat dampened at last (Powlson et al., 2016). Also, long-term data on the C-sink performance of CA systems in the humid tropics of Africa have not been presented so far.

This paper hence intends to deepen our understanding of SOC of humid tropical agro-ecosystems of SSA exposed to ISFM and CA management in the long-term. We present data from long-term trials in Western Kenya, a densely populated, intensive farming region of Kenya. New and historic soil samples were analysed to assess the impact of contrasting agricultural management practices on SOC dynamics and potentials for C-sequestration. The agronomic performance of the two trials will be published in a forthcoming paper, and therefore is not presented and discussed here.

2. Material and methods

2.1. Study area

Since 2003, the International Center for Tropical Agriculture (CIAT) maintains two long-term, researcher managed, on-farm trials in Kenya. The first trial, CT1, compares soil fertility and agronomic performance of conservation agriculture to conventional agriculture. The second trial, INM3, focuses on Integrated Soil Fertility Management (ISFM). Both trials are located in Western Kenya, 50 km northwest of the city of Kisumu. CT1 is at 0° 7′46.96″N, 34°24′19.15′E and INM3 at 34° 24′ 13.7′ E 00° 08′ 38.3″ N. They are 1.6 km apart at an altitude of 1330 m above sea level. The climate in the study area is sub-humid with a mean annual temperature of 22.5 °C and annual rainfall between 1200 and 2206 mm (average 1727 mm; observation period 1997–2013) distributed over two rainy seasons: the long rainy season lasts from March until July and the short rainy season from September until January. Maize (*Zea mays*) is the dominant staple crop in this region and is often grown in intercropping with food legumes such as common bean (*Phaseolus vulgaris*) or, more recently, soybean (*Glycine max*). The soils in the two sites are classified as Acric Ferralsols, with a clay content of between 56% (topsoil) and 84 % (subsoil; Table 1), low CEC and high aluminium saturation, a pH between 4.9 and 5.5, and a topsoil organic matter (SOM) content of between 30 and 45 g kg^{-1}. Major growth limiting nutrient are – in the order of importance – phosphate (P), nitrogen (N) and potassium (Kihara and Njoroge, 2013).

Table 1
Soil texture and bulk density of the soil profiles at INM3 and CT1 (Jelinski et al., unpublished); bulk density was measured taking undisturbed samples (n = 3 each) by driving 100 cm^3 steel rings horizontally into the mid of the respective layer using an Eijkelkamp open ring holder and plastic hammer.

Soil layer	Sand	Clay	Silt	BD
(cm)	—— (g 100 g^{-1}) ——			(g cm^{-3})
INM3				
0 – 19	26	56	18	1.10
19–60	10	82	8	1.24
60–110	8	84	8	1.10
110–171	6	84	10	1.26
171–194	26	64	10	1.32
CT1				
0 – 8	24	58	18	1.09
8–40	14	72	14	1.11
40–91	10	82	8	1.17
91–168	12	80	8	1.09
168–195	12	76	12	n.d.

While soil erosion is common in the humid tropics including Western Kenya, the two CIAT long-term trials are located on almost perfectly flat land, and hence loss of topsoil in response intensive rainfalls and surface runoff is not a concern.

According to the owner of the field, INM3 had been under a grass-shrub fallow for an unknown length of time until 2003. Fallow species included the invasive, perennial shrub *Lantana camara*. At the beginning of 2003, the site was manually cleared by the farmer for conventional cultivation of maize without inputs of organic or mineral fertilizer for one year. CT1 had been under maize from 1992 to 1994 (unfertilized), then left fallow for 6 years, after which it was cultivated again with maize until 2004 (8 seasons), but this time with seasonal inputs of around 100 kg ha^{-1} di-ammonium phosphate fertilizer.

2.2. Experimental setup

Both long-term trials are laid out in a split-split–split plot design with four reps (blocks), 44 treatments and 192 plots in total. Each plot measures 4.5 m × 6 m. CT1 has two tillage systems – zero tillage (0T) and conventional tillage (CT) – as main plots, and two residue (R) levels as sub-plots, one on which 2 t ha^{-1} maize stovers are retained (R +) and the second one where all residues are removed after harvest (R-). Sub-sub-subplots are three cropping rotations, namely continuous maize (M-M), soybean-maize rotation (M-S or S-M) and continuous maize-soybean intercropping (MS). In the following, S-M indicates the rotation where soybean is grown in the long rainy season followed by maize in the short rainy season, while M-S denotes the inverse. INM3 has an analogous layout to CT1, but with a different focus. The first split encompasses plus (4 t dry matter per ha per season) or minus farm yard manure (FYM) application, and the second split factor addresses – as CT1 does – residue retention (2 t ha^{-1} maize stover retained vs. all stover removed). The third split factor comprises three crop rotations, continuous maize (M-M), Tephrosia–maize (T-M or M-T; notation analogous to S-M/M-S in CT1) rotation, and maize-soybean intercropping (MS). *Tephrosia* (family *Fabaceae*) is a legume genus that comprises more than 20 different perennial species. We used *Tephrosia candida*, which is one of the poisonous species of *Tephrosia* for its high concentration of rotenone, and which is common in the region and seeds easily available.

Plots of CT1 as well as INM3 received between 0 and 90 kg N ha^{-1} per season as urea and 0 or 60 kg P ha^{-1} per season as triple super phosphate, with individual levels aliased with the crop rotation treatments. All plots also received 60 kg potassium ha^{-1} per season in the form of muriate of potash. In INM3, phosphate, potassium and 1/3 of

the urea fertilizers were applied at planting by broadcasting and then incorporated into soil with a hand hoe during conventional land preparation. In CT1, these fertilizers were point-place next to the planting holes – in the case of urea to the maize plants only – and incorporated carefully with a hand hoe. In both trials, the remaining 2/3 of the N-fertilizer was surface-banded next to the maize plants and then also incorporated into the soil when maize reached knee height.

The mineral N and P fertilizer application rates were:

- CT1 *and* INM3: no mineral N (N0), 30 kg N (N30), 60 kg N (N60) and 90 N ha^{-1} per season (N90) to the continuous M-M treatments, each together with 60 kg P ha^{-1} per season (P60);
- CT1 *and* INM3: N0 P60 to the continuous MS-intercropping treatment;
- INM3 only: N0 P0 (implemented twice, i.e. N = 81), N0 P60 and N30 P60 to the T-M and M-T rotations;
- CT1 only: N0 P0, N0 P60 (implemented twice, i.e. N = 8) and N60 P60 to the S-M and M-S rotation.

Agronomic management practices for CT1 are provided in details by Kihara et al. (2012), and were the same for INM3. In short, land preparation in all conventional tillage treatments was done by common hand hoeing practice to maximum 20–30 cm depth, with soil disturbance and mixing diminishing with depth. Zero tillage was restricted to opening of planting holes with a hoe and light surface-scratching with a manual weeder (about 3 cm deep) to remove weeds. Throughout the 13 years maize, soybean and Tephrosia were planted between end of March and end of April in the long-rain season, and between beginning of September and beginning of October in the short-rain season. Maize and soybean were harvested between mid-August and mid-September and beginning of February and mid-March in the long- and short-rain season, respectively. While soybean stovers were left in the field, maize stovers were removed after harvest and then 2 t ha^{-1} re-applied a few days before planting by broadcasting on the soil surface. This was done to reduce the significant loss of residues during the dry season through consumption/removal by termites. This however meant that in the 0T treatments of CT1, the soil was bare for a few weeks in-between the two seasons. Tephrosia was only harvested a few days before land preparation of the subsequent season, and biomass chopped and spread on the soil immediately. All Tephrosia material was subsequently manually incorporated into the soil. The same was done with maize stovers in the R+ sub-plots of INM3 and the CT-plots of CT1. Farm yard manure, mineral P and potassium fertilizer was applied at planting by broadcasting and incorporation into the soil by hand hoeing (together with the residues, if applicable).

2.3. Soil and agronomy measurements

From 2004 onwards, topsoil samples (N = 1) from 0 to 15 cm depths were taken twice a year in-between seasons on all 192 plots using an Edelman clay auger. Samples were oven-dried, 2-mm sieved and stored for future analysis. INM3 topsoil samples of September 2005, 2007, 2009, 2011, 2013 and 2015, and topsoil sample of CT1 from September 2006, 2009, 2012 and 2015 were analysed from March to May 2016 for total C and N by total (Duma-type of) combustion technique using an elemental macro-analyser (*Elementar Vario Max Cube*). INM3 soil samples from 2013 had already been analysed in 2014 with the same analyser. At that time about 2000 mg of soil were used per analysis, while later-on (2015 onwards) the amount of soil per analysis had been reduced to 800 mg. This reduced amount turned out sufficient for precise analysis at reduced cost. To rule out any analysis bias in response to this change of lab-practices, 36 of the 192 soil samples from 2013 were re-analysed also in 2016. Cross-comparison revealed high-level of accuracy of, and confidence in, the elemental analysis with an average deviation between the two analyses of merely 2.2%. As the soils under study are acid, it can be assumed that total carbon (TC) only consists of soil organic carbon (SOC) compounds while inorganic carbon is absent, i.e. TC = SOC.

On 18 March 2016, soil profile samples (N = 4) were collected from 0 to 15 cm, 15–30 cm, 30–50 cm, 50–75 cm, 75–100 cm in the two INM3 treatments FYM+ R+ T-M N30 P60 and FYM- R- M-M N0 P60 and analysed for SOC and total N. We anticipated that these two treatments were the most contrasting ones as far as SOC dynamics are concerned. Initial profile samples of both long-term trials were not available for inclusion into our analysis. In this paper, we will focus on describing and discussing SOC data, while total N and CN ratio data are described in the Supplementary information attached to this paper.

2.4. Statistical analysis

2.4.1 SOC, total N, and the CN ratios were tested with the GenStat (14) software for treatment difference by analysis of variance (ANOVA) using the sampling years as repeated measure. The corresponding GenStat syntax was: TREATMENT = Factor1*R*(ROT/NP) and BLOCK = Rep/Factor1/R/ROT/NP. Factor1 denotes either the two levels of tillage (CT1) or farm yard manure (INM3), R the two crop residue levels, ROT the crop rotation levels, and NP the fertilizer levels. Linear regression analysis was used to describe the changes of SOC, N and CN ratios over time (2005–2015) using years-after-onset of the trials as x-variables. The significance of the slope, i.e. whether it was different from zero, was verified with a *t*-test. Subsequently, using the linear regression equations, SOC contents ($\hat{y}$) were predicted for year 12 (2015) after the onset of the trials, and the upper and lower 95 % and 75 %-confidence interval, $\hat{y} \pm t_{crit}*S_e$, determined. Here t_{crit} is the critical value of the Student's t-$S_e = s_{yx}\sqrt{\frac{1}{N} + \frac{(x-\bar{x})^2}{SS_x}}$. These predicted, as well as the actually observed, average SOC contents of year 12, where compared against predicted (=intercept of slope) SOC contents at the onset of the trials, and the difference between the two converted into tons of C per hectare per 15 cm depth sequestered or lost over the 12 years of the trial. The soil profile SOC, N and CN ratios of the two selected treatments sampled in 2016 were analysed for differences by two-way (Treatment and Depth) ANOVA. Comparing SOC stocks and losses of different tillage systems as we did for the CT1 long-term trial, usually requires a correction for bulk density and depth bias error (see e.g. Wuest, 2009). However, the analysis of soil bulk density samples taken in CT1 in the mid-year off-season of 2009 (Paul et al., 2015) did not reveal any systematic influence of tillage − such as 0T leading to soil compaction. Paul et al. (2015) reported a bulk density ranging between 1.02 and 1.12 g cm^{-3} at 0–15 cm depth, which encompasses the average bulk density of CT1 (Table 1) used in our calculations of total losses of SOC and N at 0–15 cm. Thus in our case the equivalent mass did not change and no correction was required.

3. Results

3.1. Integrated soil fertility management (INM3 long-term trial)

FYM had no significant effect on 0–15 cm SOC contents in the INM3 trial across the six observation years (F-probability = 0.116; ANOVA table attached as Supplementary information). On the other hand, maize stover residue management, i.e. retaining (R+) or removing (R-) residues, and crop rotation had a significant effect on SOC. Whereas removing residues reduced SOC contents (R+ = 22.1 g kg^{-1}, R- = 21.3), SOC contents significantly increased in the order *continuous maize* < *maize-soybean intercropping* < *maize-Tephrosia* < *Tephrosia-maize rotation* (M-M = 20.7, MS = 21.4, M-T = 22.2 and T-M = 22.6 g kg^{-1}; LSD = 0.50). Furthermore, the ANOVA showed a significant interaction between residue management and crop rotation: Residue retention did not impact SOC in M-M, while in the other crop rotations retaining maize stovers significantly increased SOC. Moreover, the ANOVA revealed a significant time trend. Across all

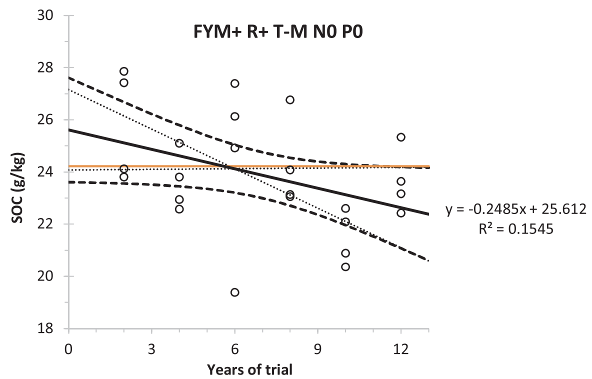

Fig. 1. Linear regression of the changes of topsoil SOC over time in the FYM+ R+ T-M N0 P0 treatment; dots are observations; straight lines are the linear regression (thick) and the lower and upper confidence intervals of the slope (dotted), respectively; curved lines are the lower and upper confidence interval of the regression; and the straight horizontal orange line denotes the intercept of the SOC linear regression of the entire trial (= 24.2 g kg^{-1}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

INM3 treatments SOC reduced linearly from 23.6 g kg^{-1} in 2005 to 20.2 g kg^{-1} in year 2015 (slope of the linear regression = −0.3627 ± 0.02 yr^{-1}, intercept = 24.2 ± 0.1 g kg^{-1}, R^2 = 0.33). Assuming − in the absence of initial data − that the intercept provides a reasonable approximation of SOC contents at the onset of the trials, the losses of SOC of the considered top 15 cm of soil over the 12 years of the entire trial was 6.65 t C ha^{-1}.

The slopes of the linear regression equations had a negative sign for all 44 treatments, and the slopes were significantly below zero for all but the FYM+ R- T-M N0 P0 and the FYM+ R+ T-M N0 P0 treatments. But, even in the latter two cases the upper 95 % confidence interval of the regression equations predicted a SOC value for year-12 (2015) not surpassing the 24.2 g kg^{-1} intercept which was used as initial SOC for the calculation of losses of SOC (Fig. 1).

This meant that in all 44 treatments a possibility of an increase in SOC amounts in the upper 15 cm of soil could be excluded. The ANOVA also showed a significant Time x FYM interaction: not applying FYM led to a faster decrease in SOC, and as a consequence eventually in 2015 differences between FYM- and FYM+ were significant (Fig. 2, upper left). In terms of SOC amounts in the top 15 cm, these differences amounted to 0.36 t C ha^{-1} in 2005 and 3.37 t C ha^{-1} in 2015. Likewise, the Time × Rotation interaction was also significant because of slightly increasing differences in SOC contents of the four rotations over time and the T-M and M-T lines crossing in 2008 (Fig. 2, upper right). In 2015, SOC of all rotations differed significantly. Time x Residue interactions, on the other hand, were not significant; differences were roughly the same throughout and significant from 2005 onwards (Fig. 2, lower left).

In 2015 the difference between R+ and R- amounted to 1.5 t C ha^{-1} 15 cm^{-1}. The combined effect of manure and residue management is shown in the lower right part of Fig. 2. Differences between the four FYM x R combinations were significant in 2015. The FYM+ graph (Fig. 2 upper left) shows a notable dent in the curve at year 2013. As such dent is absent in the FYM- graph, we believe – but cannot be entirely sure in the absence of comprehensive manure quality data − that this is a consequence of manure application of poor quality in an unknown number of seasons before August 2013. Single available information about nutrient concentration of the applied manure in August 2013 indicated that manure of reasonable quality was applied at this point in time (see Table 3 in the supplemental information). Within the M-M rotation, the difference in SOC contents (Δ = 0.38 g kg^{-1}) between N90 and N0 was not significant (same for N90 vs. N30 or N60), irrespectively of whether FYM was applied or residues were retained. On the other hand, omitting P-fertilizer in the P0 treatment of the T-M or M-T rotation in comparison to the P60 treatment (N0 or N30) led to significantly lower SOC content averaged across all years. However, these differences were small, and after 12 years, no significant distinction could be made. Also, the slopes of the linear regression equations describing trends over time were not significantly different from each other comparing SOC contents by FYM and residue treatments.

Converted into total amounts, losses SOC over the observed 12-year period were high, ranging on average between 2.6 and 11.5 t C ha^{-1}, i.e. 0.21 and 0.96 t C ha^{-1} yr^{-1}. There was a tendency of higher losses if FYM and crop residues where not applied or retained and inputs of green manure (Tephrosia) absent (Fig. 3).

Losses surpassed 10 t C ha^{-1} in all M-M rotations within the FYM-R- or R+ treatments, i.e. more than 0.75 t C ha^{-1} per year on average. Losses in this rotation were still notable (> 6 t C ha^{-1} or 0.46 t ha^{-1} yr^{-1}) even if FYM was applied, and the mitigating effect of residue retention, even though applied two times per year in this rotation, was insignificant. Calculating SOC changes merely by comparing initial, extrapolated 2003 SOC contents and average observed 2015 data − i.e. largely omitting the linear regression and confidence interval analyses − yielded losses that were in the majority of cases somewhat lower than average linear regression results (dots in Fig. 3). This in part was a consequence of the slightly improving SOC trends after the dip in 2013 in the FYM+ treatments. Avoided losses by adopting FYM application alone ranged between 2.0 and 6.0 t C ha^{-1}, i.e. 0.16 and 0.50 t C ha^{-1} yr^{-1} (average 0.26 t C ha^{-1} yr^{-1}).

3.2. Conservation agriculture (CT1 long-term trial)

Time was the only major factor that significantly influenced topsoil organic carbon contents in CT1 (ANOVA table attached as Supplementary information). Across all treatments SOC reduced linearly from 20.2 g kg^{-1} in 2006 to 18.8 g kg^{-1} in year 2015 (slope of the linear regression = −0.16 ± 0.01 yr^{-1}, intercept = 20.8 ± 0.10 g kg^{-1}, R^2 = 0.18). With overall 3.2 t C ha^{-1} 15 cm^{-1} cm per 12 years, the decrease of SOC over time was considerably smaller than that observed in INM3. From the 44 treatments, the slopes of the linear regression equations of only 21 were significantly less than zero. For the remaining 23 treatments it could not be ruled out at $p \le 0.05$ that SOC did not decrease from 2006 to 2015. Neither tillage nor residue management nor crop rotation did significantly impact SOC in this trial (Fig. 4).

The ANOVA detected some significant interactions, namely Tillage × Time, Tillage × R × Time and Tillage x Rotation × Time (Fig. 4 lower right). This was a result of a significantly higher SOC contents of the 0T R+ MS and 0T R+ S-M treatments but in 2009 only. In 2015, comparing the various Rotation/Fertilizer sub-sub-treatments within the same level of tillage and residue management, neither of them stood out with significantly higher or lower SOC contents. Yet, comparing all 44 treatments, in 2015 the 0T R+ MS N0 P60 (19.9 g kg^{-1}) treatment had a significantly higher SOC content than the 0T R- M-S N60 P60 (17.9 g kg^{-1}) and 0T R- S-M N0 P0 and (17.9 g kg^{-1}; LSD = 1.9 g kg^{-1}) treatments.

Even though slopes describing the linear trend of SOC from 2005 to 2015 were often not significantly different from zero, nevertheless total SOC losses were significant in all but three cases (Fig. 5).

This apparent contradiction was the consequence of using the overall intercept value (20.8 g kg^{-1}) of SOC as reference for calculating losses of SOC from the onset of the trial. However, SOC often had decreased already in the first three years for which no data were available for inclusion in the regression analysis, the slope of which then was flatter than if the intercept had been fixed at 20.8 g kg^{-1}. The three exceptions were treatments where zero tillage was practiced and 2 t ha^{-1} maize stover residues retained, namely the rotations 0T R+ M-M N30 P60, 0T R+ M-S N60 P60 and 0T R+ S-M N0 P0. Total losses ranged between 1.4 and 4.8 t C ha^{-1}, i.e. 0.11 and 0.37 t C ha^{-1} yr^{-1}. Comparing relative differences between Conservation Agriculture (CA) treatments (0T R+) and conventional farmer practice (CT R-) yielded

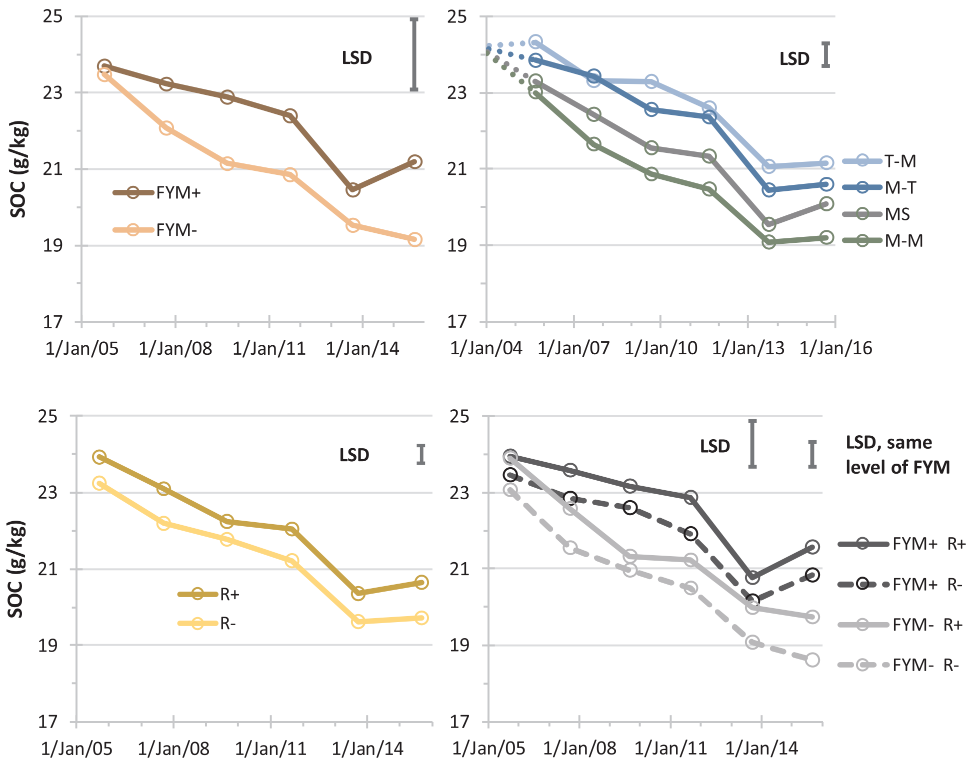

Fig. 2. Changes of topsoil organic carbon (SOC) over time in the INM3 trial response to farm yard manure (upper left), crop rotation (upper right), residue (lower left) or manure and residue management (right); dotted lines in the upper right figure illustrate the loss of SOC over the first two years of treatments assuming an initial SOC content of 24.2 g kg^{-1}.

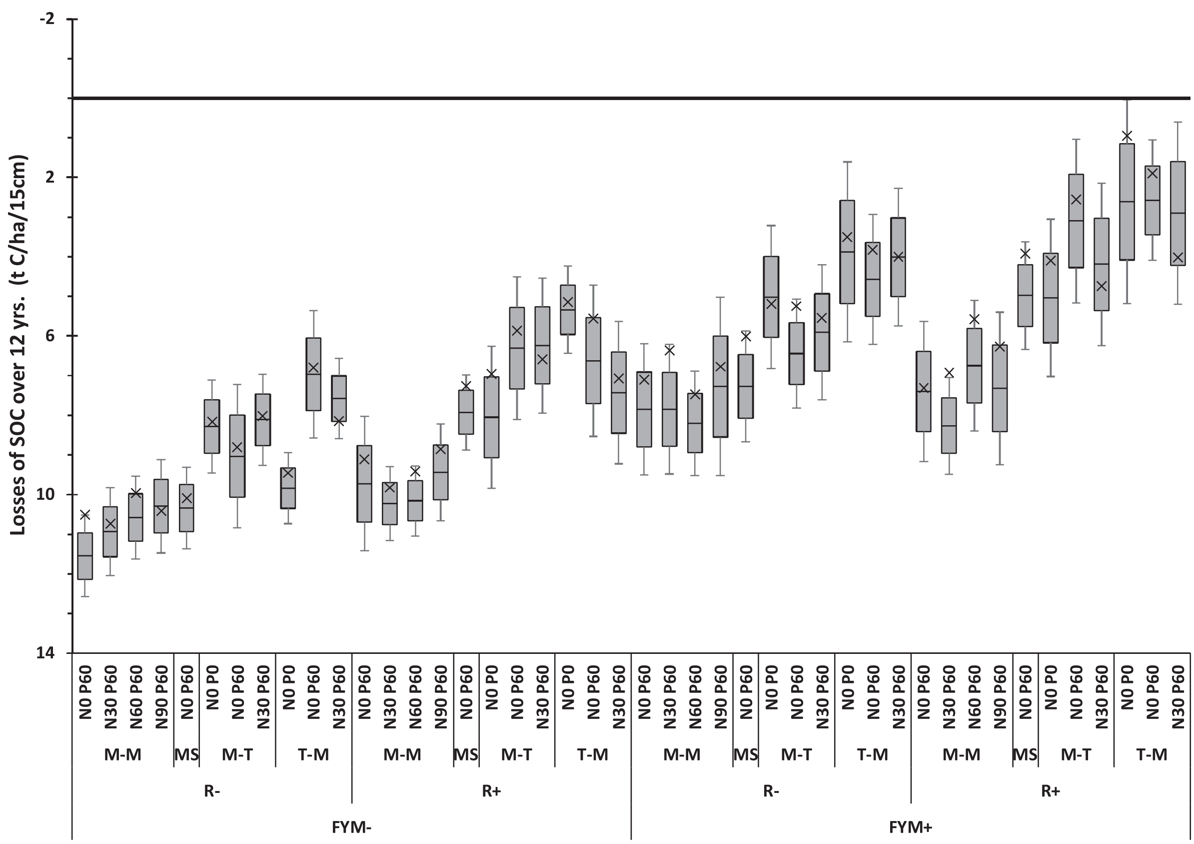

Fig. 3. Losses of topsoil organic carbon (t ha^{-1} 15 cm^{-1}) of all treatments of INM3 from 2003 to 2015; positive numbers are losses, negative numbers gains; boxes and whiskers depict the SOC losses (or gains) predicted by the lower to upper 75% and 95% confidence interval of the linear regression describing 2005–2015 downward trends of SOC, respectively; points depict the losses of SOC based only on 2015 data; both estimates use a backward extrapolated SOC content of 24.2 g kg^{-1} at the onset of the trial as a reference point.

positive figures for all 11 rotation/fertilizer CA treatments. These ranged between 0.1 and 2.9 t C ha^{-1} that weren't lost in the CA systems over the 12 years. On average this would equal 0.09 (linear regression) or 0.13 t C ha^{-1} yr^{-1} (2015 data only). Whether or not 2 t ha^{-1} of maize stovers were retained twice a year (M-M rotations and MS intercropping) or only once (M-S and S-M rotations) did not affect these

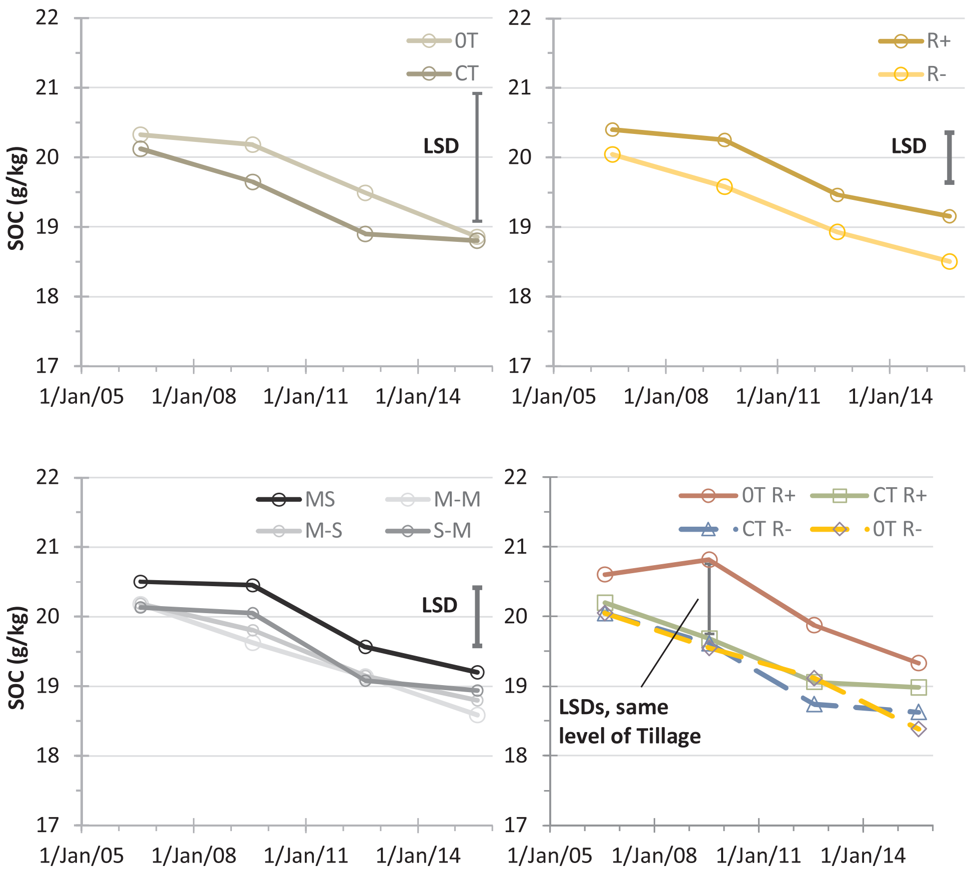

Fig. 4. Changes of topsoil organic carbon (SOC) over time in the CT1 trial in response to tillage (upper left), residue retention (upper right) crop rotation (lower left), or tillage and residue management practices (lower right).

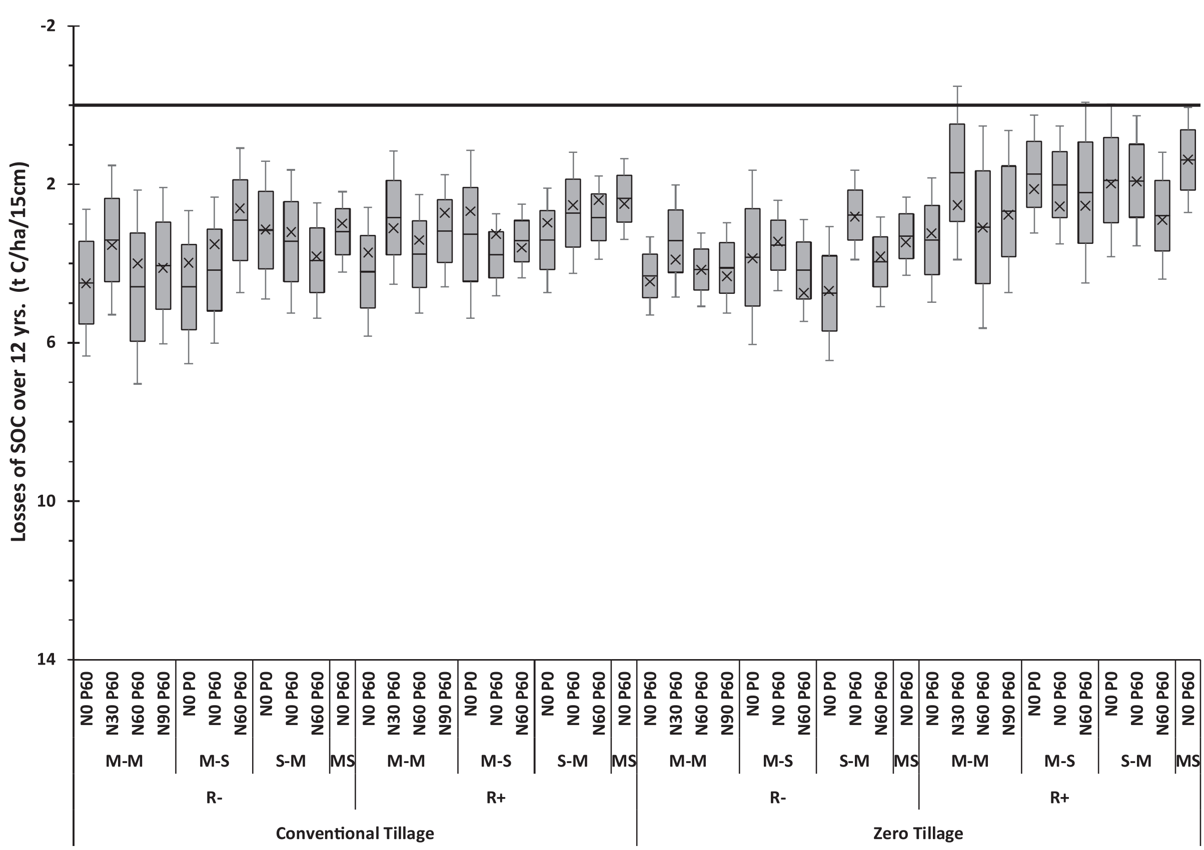

Fig. 5. Losses of topsoil organic carbon (t ha^{-1} 15 cm^{-1}) of all treatments of CT1 from 2003 to 2015; positive numbers are losses, negative numbers gains; boxes and whiskers depict the SOC losses (or gains) predicted by the lower to upper 75% and 95% confidence interval of the linear regression describing 2005–2015 downward trends of SOC, respectively; points depict the losses of SOC based only on 2015 data; both estimates use a backward extrapolated SOC content of 20.8 g kg^{-1} at the onset of the trial as a reference point.

Table 2
Soil organic carbon (SOC) contents (g kg^{-1}) and differences in SOC amounts (t ha^{-1}) from 0 to 1 m depth of the two INM3 treatments FYM+ R+ T-M N30 P60 and FYM- R- M-M N0 P60 in March 2016.

Soil depth	SOC			ΔSOC
	FYM+ R+ T-M N30 P60		*FYM- R- M-M N0 P60*	
(cm)	– - (g kg^{-1}) – -			(t ha^{-1})
0–15	20.9		17.0	6.3
15–30	18.6		16.0	4.5
30–50	15.0		13.0	4.9
50–75	10.1		9.5	1.9
75–100	7.0		7.1	−0.2
Sum				**17.4**
LSD				
Treatment		0.7		
Depth		1.1		
Trt. x Depth		1.6		

"avoided losses", which is not surprising as soybean residues were fully retained, thus to some extent substituting for absent maize stover residues.

3.3. Soil profile data

The two contrasting management treatments of INM3, FYM+ R+ T-M N30 P60 and FYM- R- M-M N0 P60, for which soil profile samples to 1 m depth were collected in March 2016, differed significantly in their SOC to a depth of 50 cm (Table 2).

With 20.9 and 17.0 g kg^{-1}, the topsoil (0–15 cm) SOC contents were close to the 2015 data of both treatments presented above. Both were significantly lower than the estimated SOC content at the onset of the trial (24.2 g kg^{-1}). Corresponding losses amounted to 5.4 and 11.7 t C ha^{-1}, i.e. an equivalent of 0.42 and 0.90 t C ha^{-1} yr^{-1} for the FYM+ R+ T-M N30 P60 and FYM- R- M-M N0 P60 treatment, respectively. The difference between the two treatments was 6.3 t C ha^{-1} in 0–15 cm. The soil layers from 15 cm to 1 m added 11.1 t C ha^{-1} (equivalent to 0.85 t C ha^{-1} yr^{-1}) to the overall treatment difference which was 17.4 t C ha^{-1} per the entire 1 m soil profile.

3.4. Cross-trial comparison

Both long-term trials are located very close to each other, and thus have equal climate and soils. Furthermore, some of the treatments of both trials are identical, namely those of conventional tillage, no application of manure and continuous maize cultivation with varying fertilizer-N levels. A cross-site comparison of these treatments thus provides further insights into long-term dynamics of soils with different initial topsoil organic carbon contents as the earlier analysis had revealed. Fig. 6 shows that the SOC contents at 0–15 cm depth of both trials approached equal levels 8–9 years after the onset of the trials.

The confidence intervals of the linear regression of SOC of the selected treatments of both trials start overlapping 2012 onwards. In 2015 SOC contents ranged between 17.9 and 18.8 g kg^{-1}. The R- treatments almost consistently had lower SOC than the R+ treatments, but differences were not significant. The confidence intervals for CT1 encircled displayed treatment averages entirely, indicating that a linear trend described the loss of SOC over time adequately in this trial, while this was less so for INM3, were losses of SOC tended to slow down over time.

4. Discussion

The results of our long-term study show that neither CA nor ISFM fulfilled the promise of increasing SOC over time. The contrary, in general SOC contents in the top 15 cm decreased, even if ISFM and CA is practiced. Retention of 2 t ha^{-1} maize residues – twice per year in the continuous maize treatments – was not sufficient to increase SOC, i.e. such management practice could only slow down the loss of SOC over time. For example, R+ treatments tended to have higher SOC contents throughout (significant in INM3). This 2 t ha^{-1} of residues is equivalent to about 30–40 % of the average seasonal total maize stover produced in our trials, but it may be as much as 100 % of the maize stover usually produced on farmers' fields in Western Kenya. As has been shown by Margenot et al. (2017), organic matter inputs of 2 t ha^{-1} crop residue retained in CT1 induced an increase in microbial (enzyme) activity. These inputs also increased the abundance of *meso*- and macro-fauna, especially of termites feeding by foraging (Kihara et al., 2015; Ayuke et al., 2011). Such elevated activities prevented a gross build-up SOM that could slow down SOC losses. Besides, earlier studies revealed an absence of a measurable protection of SOC in soil aggregates leveraged through CA despite the increased soil aggregate stability (Paul et al., 2013; Kihara et al., 2012). Although it has been argued that SOC could potentially be increased by increasing organic matter inputs (Margenot et al., 2017), this may still be hindered by the 1:1 kaolinite clay type predominating in western Kenya (Kihara et al., 2012). Clay content and type are considered important determinants of C sequestration potential, with 2:1 clay soils having increased ability of carbon protection relative to 1:1 kaolinites (Bationo et al., 2007). Thus, it cannot be ruled out that carbon loss maybe slower (or even carbon accumulation occurring) in tropical environments where 2:1 clay types dominate. In any case, increasing organic matter inputs seems prohibitive in Western Kenya where smallholders in the majority of cases have mixed crop-livestock enterprises, and ruminant feed – including maize stover – is a limited resource (Erenstein, 2003; Valbuena et al., 2012).

The dent in the INM3 FYM+ SOC graph at year 2013 (Fig. 2, upper left), is most likely a result of application of manure of poor quality, as this drop in SOC is absent in the FYM- graph. Even though unintended, it reveals an interesting aspect, namely that 'sub-optimal' ISFM is quickly visible, and not buffered by a supposedly higher resilience that the ISFM system would have acquired after 10 years of 8 t manure ha^{-1} yr^{-1} application, improved varieties and in most treatments even mineral fertilizer application rates that qualify at least as sufficient (as far as the loose concept of ISFM allows such judgement). Nevertheless, repeated manure application of 4 t ha^{-1}, on the other hand, did slow down SOC losses in INM3 witnessed by an increasing difference in SOC contents over time comparing FYM+ and FYM- and thus a significant Time x FYM interaction. As manure is a more readily available resource in mixed crop-livestock smallholder systems, manure application proved a viable strategy to reduce SOC losses. Whether manure would be an additional benefit for CA remains to be tested, as this would come at the cost of some soil disturbance during manure incorporation.

There is no evidence of mineral N and P fertilizer application mitigating (or slowing down) losses of SOC over time, as is sometimes reported (The World Bank, 2012), nor speeding up decomposition as some argue to be an inevitable downside of chemical fertilizer use in the tropics (Kotschi, 2013). Thus, our observation are in line with that from a long-term trial in the USA (Khan et al., 2007).

Limited effects of CA on SOC contents was also reported more recently by Cheesman et al. (2016; Powlson et al. (2016, and some eight years ago by Govaerts et al. (2009. De Sant-Anna et al. (2016) also reported very limited response of 0T and fertilizer + lime application after 22 years of cropping in the Brazilian Cerrado. Others, on the other hand, testified a beneficial impact of improved management on soil C (The World Bank, 2012; Anyanzwa et al., 2010; Chivenge et al., 2007; Bationo et al., 2007).

Almost all of these studies however, have one thing in common: they do not trace SOC dynamics over time but merely compare treatment differences – often the improved practice (e.g. ISFM or CA) against what would supposedly be farmer's practice. While this allows for determining "avoided losses", it does not provide evidence of a net

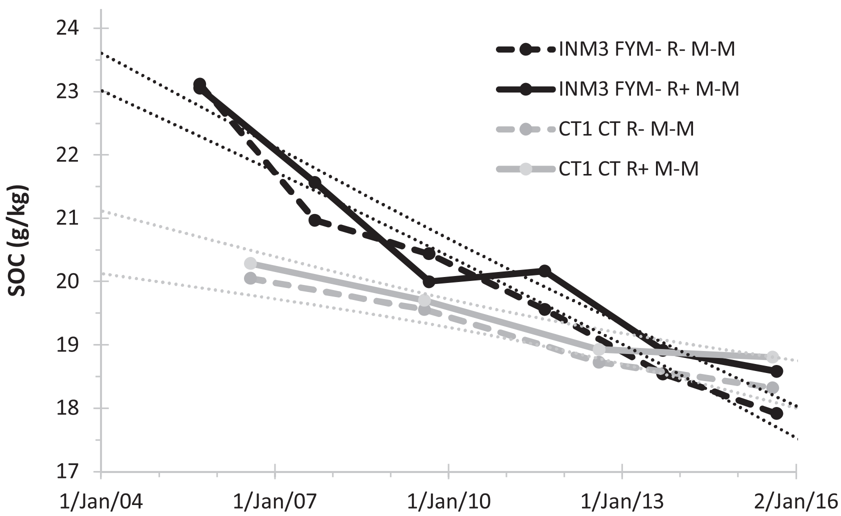

Fig. 6. Changes of topsoil organic carbon of identical (conventional agriculture) CT1 and INM3 treatments, i.e. conventional tillage, no application of manure and continuous maize cultivation with 0 to 90 kg N ha^{-1} mineral fertilizer applied; dotted thin curves are the lower and upper confidence interval of the linear regression of CT1 (N = 128) and INM3 (N = 192) data with both residue levels combined.

sequestration of SOC. It is interesting that, despite this important distinction, all these studies use the term sequestration – "*The process of removing carbon from the atmosphere and depositing it in a reservoir.*" (United Nations Framework Convention on Climate Change, 2017), even though acknowledging that "*all soil carbon sequestration rates are estimates of effect size – the difference with respect to a control—and thus represent the marginal benefit of adopting that practice*" (The World Bank, 2012).

Missing soil profile samples at the onset of the trial and thus the absence of initial, reference soil data poses a challenge. Without such data it is difficult − but not impossible − to discuss absolute losses of SOC, or potential SOC sequestration. Regression analysis of available 2005–2015 data from INM3 suggested that the SOC content in 0–15 cm decreased in all but two treatments; the latter including FYM+ R+ T-M N30 P60 for which 1 m soil profile data was collected in 2016. This is actually the treatment with the highest levels of inputs: on average 7 t DM Tephrosia biomass (Sommer et al., 2016a), 8 t manure, 2 t maize stover, 60 kg N, 120 kg P and 120 kg K mineral fertilizer per hectare and year. Assuming that the FYM+ R+ T-M N30 P60 treatment could fully maintain initial SOC levels below 15 cm depth over the considered 13 years, and furthermore assuming that the contrasting FYM- R- M-M N0 P60 treatment describes the worst case scenario of SOC losses observed within INM3, then the annual top 1 m SOC losses of the remaining treatments ranged somewhere between very little (all T-M or M-T rotation within FYM+ R+) to up to 1.75 t C ha^{-1} yr^{-1}, which is the sum of 0.90 t C ha^{-1} yr^{-1} of 0–15 cm and 0.85 t C ha^{-1} yr^{-1} of 15–100 cm soil depth. It is possible that the continuous application and incorporation into the soil of the aforementioned significant amounts of inputs increased the SOC at 15–30 cm depth over initial conditions in FYM+ R+ T-M N30 P60. This would mean that losses of SOC over the 13 years for some treatments could have been lower than the 1.75 t C ha^{-1} yr^{-1} outlined above. Yet, own observations showed that most of the manure, maize and Tephrosia biomass incorporated by simple hand hoeing ended up in the topsoil, and only little actually reached 30 cm. Also, soil temperatures and moisture were favourable for decomposition at 15–30 cm depth. This means that an actual sequestration of C in deeper soil layers in the FYM+ R+ T-M or M-T treatments seems unlikely, unless triggered through bioturbation, leaching of dissolved organic matter, or an elevated input of root biomass at this depth.

Comparison of the two long-term trials showed that the INM3 site lost SOC at a faster rate than the CT1 site, at least the first 8–9 years. It seems logical to assume that this is the effect of the land use history before the onset of the trials, as the 13-year long agronomic management for the compared treatments (Fig. 6) was absolutely identical. Our limited information of the land use history seems to support this hypothesis: CT1 was under 4 years of conventional continuous maize cropping before the onset of the trial, while for INM3 this was only 1 year preceded by 8 years of a bush-grass fallow. This however also means that most likely CA (0T R+) treatments if installed on a soil with a land use history identical to INM3, would probably have lost more SOC than they actually did. Hence, net losses of SOC can be the same on a very poorly managed field and on a perfect ISFM field. For instances, the CT1 treatment that was conventionally tilled, had all residues removed and maize continuously planted for the last 13 years without any mineral N inputs (CT R- M-M N0 P60) − and thus would qualify as a very poorly manged field – lost 4.5 t C ha^{-1} over the considered 12 years, while our perfect ISFM treatment that annually received 8 t ha^{-1} manure, had a 7 t ha^{-1} Tephrosia green manure cover crop included into the rotation once a year, 2 t ha^{-1} maize stover retained and received 60 kg N and P ha^{-1} as mineral fertilizer annually (FYM+ R+ M-T N30 P60) also lost 4.2 t C ha^{-1}. Thus, clearly the initial soil status, i.e. the absolute amounts and probably the quality of soil organic matter, as a result of differing land use history, was the driver of the bulk of the SOC losses and less so the actually implemented agronomic management practices.

However, this in return also means that highly degraded soils, unless degraded beyond repair, are probably soils where true carbon sequestration could be achieved more easily than in fertile soils where SOC levels are close to natural equilibrium levels. It remains however to be discussed whether its rewarding to put policies in place – e.g. payments for environmental services – that disfavour farmers that have adopted more sustainable land management practices early on, reasoning that there are no further gains to be made.

Soil erosion and loss of carbon-rich(er) topsoil can confound the issue of soil carbon sequestration significantly. Our long-term trials are located on almost perfectly flat land, and surface runoff and soil erosion is not an issue. But, it certainly is in Western Kenya with its predominantly sloped landscape. It is however beyond the scope of this publication to estimate the importance of landscape position, or efforts of land restoration and avoidance of soil erosion on the soil carbon balance and potential sequestration.

Our prevented losses of SOC under CA are at the lower end of the figures presented by Powlson et al. (2016), who compared CA with business-as-usual, CT systems for sub-Saharan Africa. Our data support their conclusion that '*in many cases CA practices will deliver only a small degree of climate change mitigation through soil carbon sequestration*'. Interestingly, even though very comprehensive, the *meta*-analysis of Powlson et al. (2016) did not elaborate on the importance of preceding land use history. They however pointed out the importance of equal soil mass sampling and of a stratification of SOC with depth that often comes with 0T. Repeated routine soil sampling in our trials did not account for such stratification, but such assessments had been done

earlier in CT1 (Kihara et al., 2012). Even with that stratification, neither were total carbon stocks in the 0–5 cm and 5–20 cm depth affected by tillage, crop residue or cropping system as also observed in the current study (Kihara et al., 2012).

As outlined above, C sequestration in soils of the humid tropics of Africa seems a challenge especially given the high prevalence of low activity (1:1) clays. But, that does certainly not render some four decades of research on sustainable, soil conserving agricultural management practices useless. Our long-term trials clearly show the superior effect of such good practices on crop productivity, whereas ISFM and CA practices outperform common farmer practices two to threefold (data not shown here). The primarily focus of such agronomic, biophysical research of centres like CIAT and national partners is increasing and stabilizing the food security of smallholder farmers, contributing to improving livelihoods. The issue of soil organic carbon sequestration and associated climate change mitigation is gaining in importance these days, but is still considered a co-benefit only. Or, in other words, we primarily promote *using* SOM, while replenishing losses, rather than *hoarding* it for the sake of sequestration only (compare Janzen, 2006).

5. Conclusions

Our research shows that ISFM and CA in the humid tropical agroecosystem of Western Kenya proved unsuccessful in sequestering – in the true sense of the meaning – carbon in soils. Notwithstanding, these technologies do help avoiding SOC losses and thus contribute to climate change mitigation. In that respect, the imprecise use of the term 'C-sequestration' in the literature poses a challenge to formulating a clear message to policy makers. Many publications use it as a loose substitute to describe avoided losses, while only a few actually provide evidence of soils as a true net C-sink. Reducing C-losses from soils can help make agriculture become carbon neutral, if such reductions are not offset by increased emissions of e.g. nitrous oxide. However, reducing losses does not serve offsetting greenhouse gas emissions elsewhere, as currently policy makers may have in mind when supporting global initiatives such as 4p1000.

Our trials show that 'doing more' could potentially revert negative SOC trends. There is scope for an uninterrupted and full soil surface coverage, which has been proven to be of chief importance for CA to fully function (Hobbs et al., 2008). This could be achieved by inclusion of ground-covering, relay-planted herbaceous cover crops. Furthermore, deep rooting perennials, preferably forage grasses and agroforestry species, have larger acceptance by mixed crop-livestock smallholders than Tephrosia that has no added food or feed value. While such 'best bets' have repeatedly been shown to outperform traditional systems, for a range of reasons the adoption rate is still limited (Sommer et al., 2016b). We believe that carbon trading and related payments for environmental service (PES) could provide an entry point to leverage uptake by farmers, as these could for example compensate for increased upfront investments (e.g. through input credits) or remove pending risks (e.g. through crop, weather or livestock insurance). To be successful, global initiative like 4p1000, but also such addressing land restoration more broadly (e.g. AFR100 or 20 × 20), should embrace PES schemes into their plan of actions.

Acknowledgements

We are grateful for funding for this study from the Federal Ministry for Economic Cooperation and Development (BMZ), Germany. This research was/is carried out under the CGIAR Research Program on Water, Land and Ecosystems with support from CGIAR Fund Donors including: the Australian Center for International Agricultural Research (ACIAR); Bill and Melinda Gates Foundation; Netherlands Directorate-General for International Cooperation (DGIS); Swedish International Development Cooperation Agency (Sida); Swiss Agency for Development Cooperation (SDC); and the UK Department of International Development (DIFD).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.11.004.

References

Anyanzwa, H., Okalebo, J.R., Othieno, C.O., Bationo, A., Waswa, B.S., Kihara, J., 2010. Effects of conservation tillage, crop residue and cropping systems on changes in soil organic matter and maize–legume production: a case study in Teso District. Nutr. Cycl. Agroecosyst. 88 (1), 39–47. http://dx.doi.org/10.1007/s10705-008-9210-2.

Ayuke, F.O., Pulleman, M.M., Vanlauwe, B., de Goede, R.G.M., Six, J., Csuzdi, C., Brussaard, L., 2011. Agricultural management affects earthworm and termite diversity across humid to semi-arid tropical zones. Agriculture. Ecosys. Environ. 140 (1), 148–154. http://dx.doi.org/10.1016/j.agee.2010.11.021.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration —What do we really know? Agriculture. Ecosyst. Environ. 118, 1–5. http://dx.doi.org/10.1016/j.agee.2006.05.014.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric. Syst. 94 (1), 13–25. http://dx.doi.org/10.1016/j.agsy.2005.08.011.

Cheesman, S., Thierfelder, C., Eash, N.S., Kassie, G.T., Frossard, E., 2016. Soil carbon stocks in conservation agriculture systems of Southern Africa. Soil Tillage Res. 156, 99–109. http://dx.doi.org/10.1016/j.still.2015.09.018.

Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil Tillage Res. 94 (2), 328–337. http://dx.doi.org/10.1016/j.still.2006.08.006.

De Sant-Anna, S.A.C., Jantalia, C.P., Sá, J.M., Vilela, L., Marchão, R.L., Alves, B.J.R., 2016. Changes in soil organic carbon during 22 years of pastures, cropping or integrated crop/livestock systems in the Brazilian Cerrado. Nutr. Cyc. Agroecosyst. http://dx.doi.org/10.1007/s10705-016-9812-z.

Erenstein, O., 2003. Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agriculture. Ecosyst. Environ. 100 (1), 17–37. http://dx.doi.org/10.1016/S0167-8809(03)00150-6.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit. Rev. Plant Sci. 28, 97–122. http://dx.doi.org/10.1080/07352680902776358.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363 (1491). http://dx.doi.org/10.1098/rstb.2007.2169.

Janzen, H.H., 2006. The soil carbon dilemma: shall we hoard it or use it? Soil Biol. Biochem. 38 (3), 419–424. http://dx.doi.org/10.1016/j.soilbio.2005.10.008.

Khan, S.A., Mulvaney, R.L., Ellsworth, T.R., Boast, C.W., 2007. The myth of nitrogen fertilization for soil carbon sequestration. J. Environ. Qual. 36, 1821–1832. http://dx.doi.org/10.2134/jeq2007.0099.

Kihara, J., Njoroge, S., 2013. Phosphorus agronomic efficiency in maize-based cropping systems: a focus on western Kenya. Field Crop Res. 150, 1–8. http://dx.doi.org/10.1016/j.fcr.2013.05.025.

Kihara, J., Martius, C., Amelung, W., Bationo, A., Thuita, M., Lesueur, D., Vlek, P.L.G., 2012. Soil aggregation and total bacteria and fungi diversity in various tillage systems of sub-humid and semi-arid Kenya. Appl. Soil Ecol. 58, 12–20. http://dx.doi.org/10.1016/j.apsoil.2012.03.004.

Kihara, J., Martius, C., Bationo, A., 2015. Crop residue disappearance and macrofauna activity in sub-humid western Kenya. Nutr. Cycl. Agroecosyst. 102 (1), 101–111. http://dx.doi.org/10.1007/s10705-014-9649-2.

Kotschi, J., 2013. A Soiled Reputation. Adverse Impacts of Mineral Fertilizers in Tropical Agriculture. Heinrich Böll Stiftung (Heinrich Böll Foundation). WWF Germany, pp. 58. Internet Publication, last Accessed April 2017. https://www.boell.de/sites/default/files/WWF_Mineralduenger_englisch_WEB.pdf.

Lal, R., 2003. Global potential of soil carbon sequestration to mitigate the greenhouse effect. Crit. Rev. Plant Sci. 22 (2), 151–184. http://dx.doi.org/10.1080/713610854.

Lal, R., 2010. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Security 2 (2), 169–177. http://dx.doi.org/10.1007/s12571-010-0060-9.

Lal, R., 2016. Beyond COP 21: potential and challenges of the 4 per Thousand initiative. J. Soil Water Conserv. 71, 20A–25A. http://dx.doi.org/10.2489/jswc.71.1.20A.

Margenot, A.J., Paul, B.K., Sommer, R.R., Pulleman, M.M., Parikh, S.J., Jackson, L.E., Fonte, S.J., 2017. Can conservation agriculture improve phosphorus (P) availability in weathered soils? Effects of tillage and residue management on soil P status after 9 years in a Kenyan Oxisol. Soil Tillage Res. 166, 157–166. http://dx.doi.org/10.1016/j.still.2016.09.003.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. http://dx.doi.org/10.1016/j.geoderma.2017.01.002.

OECD, 2016. What Next for Food and Agriculture Post-COP21? OECD Trade and Agriculture Directorate. Internet publication, last Accessed April 2017: https://www.oecd.org/tad/events/COP21-paris-agreement-and-agriculture-draft.pdf.

Paul, B.K., Vanlauwe, B., Ayuke, F., Gassner, A., Hoogmoed, M., Hurisso, T.T., Koala, S., Leleib, D., Ndabamenye, T., Six, J., Pulleman, M.M., 2013. Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity. Agric. Ecosyst. Environ. 164, 14–22. http://dx.doi.org/10.1016/j.agee.2012.10.003.

Paul, B.K., Vanlauwe, B., Hoogmoed, M., Hurisso, T.T., Ndabamenye, T., Terano, Y., Six, J., Ayuke, F., Pulleman, M.M., 2015. Exclusion of soil macrofauna did not affect soil quality but increased crop yields in a sub-humid tropical maize-based system. Agric. Ecosyst. Environ. 208, 75–85. http://dx.doi.org/10.1016/j.agee.2015.04.001.

Paustian, K., Babcock, B., Hatfield, J., Lal, R., McCarl, B., McLaughlin, S., Mosier, A., Rice, C., Robertson, G.P., Rosenberg, N.J., Rosenzweig, C., Schlesinger, W.H., Zilberman, D., 2004. Agricultural Mitigation of Greenhouse Gases: Science and Policy Option. Council on Agricultural Science and Technology. Report, R141. Internet Publication, Last Accessed April 2017 https://pdfs.semanticscholar.org/4ad1/c374924b9269a267ce516fa4a32826a465ca.pdf.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.F., Smith, P.P., 2016. Climate-smart soils. Nature 532, 49–57. http://dx.doi.org/10.1038/nature17174.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2014. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–368. http://dx.doi.org/10.1038/nature13809.

Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur. J. Soil Sci. 62 (1), 42–55. http://dx.doi.org/10.1111/j.1365-2389.2010.01342.x.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4 (8), 678–683. http://dx.doi.org/10.1038/nclimate2292.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174. http://dx.doi.org/10.1016/j.agee.2016.01.005.

Sanginga, N., Woomer, P.L., 2009. Integrated soil fertility management in africa: principles, practices and development processes. tropical soil biology and fertility institute of the international center of tropical agriculture. Nairobi 263.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans R. Soc. Lond. B Biol. Sci. 363 (1492), 789–813. http://dx.doi.org/10.1098/rstb.2007.2184.

Smith, G., 2016. Four Unexplored Big Wins in Agriculture: Tackling Climate Change Through Landscape Restoration. CIAT Blog, November 15, 2016. http://blog.ciat.cgiar.org/four-unexplored-big-wins-in-agriculture-tackling-climate-change-through-landscape-restoration/.

Sommer, R., Bossio, D., 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. J. Environ. Manage. 144, 83–87. http://dx.doi.org/10.1016/j.jenvman.2014.05.017.

Sommer, R., de Pauw, E., 2011. Organic carbon in soils of Central Asia—status quo and potentials for sequestration. Plant Soil 338, 273–288. http://dx.doi.org/10.1007/s11104-010-0479-y.

Sommer, R., Mukalama, J., Kihara, J., Koala, S., Winowiecki, L., Bossio, D., 2016a. Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in Western Kenya. Nutr. Cycl. Agroecosyst. 105 (3), 229–248. http://dx.doi.org/10.1007/s10705-015-9693-6.

Sommer, R., Godiah, D., Braslow, J., (2016). Soil Best Bets Compendium. International Center for Tropical Agriculture (CIAT). Available at: https://ciat.cgiar.org/soil-best-bets.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment 164, 80–99. http://dx.doi.org/10.1016/j.agee.2012.10.001.

The World Bank (2012). Carbon Sequestration in Agricultural Soils. Report No. 67395-GLB. The World Bank. Washington DC. 118 p. Internet Publication, last accessed April 2012 http://documents.worldbank.org/curated/en/751961468336701332/pdf/673950REVISED000CarbonSeq0Web0final.pdf.

Thierfelder, C., Mutenje, M., Mujeyi, A., Mupangwa, W., 2014. Where is the limit? Lessons learned from long-term conservation agriculture research in Zimuto Communal Area, Zimbabwe. Food Security 7, 15. http://dx.doi.org/10.1007/s12571-014-0404-y.

Tittonell, P., Corbeels, M., van Wijk, M.T., Vanlauwe, B., Giller, K.E., 2007. Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya: explorations using the crop-Soil model FIELD. Agron. J. 100, 1511–1526. http://dx.doi.org/10.2134/agronj2007.0355.

United Nations Framework Convention on Climate Change (2017). Glossary of climate change acronyms and terms. http://unfccc.int/essential_background/glossary/items/3666.php#C.

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A.J., 2012. Conservation Agriculture in mixed crop–livestock systems: scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. Field Crops Res. 132, 175–184. http://dx.doi.org/10.1016/j.fcr.2012.02.022.

Verhulst, N., Govaerts, B., Sayre, K.D., Sonder, K., Romero-Perezgrovas, R., Mezzalama, M., Dendooven, L., 2012. Conservation agriculture as a means to mitigate and adapt to climate change, a case study from Mexico. In: Wollenberg, E., Nihart, A., Tapio-Biström, M.L., Grieg-Gran, M. (Eds.), Climate Change Mitigation and Agriculture. Earthscan, London, England, pp. 287–300.

West, T.O., Six, J., 2007. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Clim. Change 80, 25–41. http://dx.doi.org/10.1007/s10584-006-9173-8.

Wollenberg, E., Richards, M., Smith, P., Havlik, P., Obersteiner, M., Tubiello, F.N., 2016. Reducing emissions from agriculture to meet the 2 °C target. Global Change Biology 22 (12), 3859–3864. http://dx.doi.org/10.1111/gcb.13340.

Wuest, S.B., 2009. Correction of bulk density and sampling method biases using soil mass per unit area. Soil Sci. Soc. Am. J. 73, 312–316. http://dx.doi.org/10.2136/sssaj2008.0063.